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OPTICAL AND GeV-TeV FLASHES FROM GAMMA-RAY BURSTS

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ABSTRACT

The synchrotron optical flash caught in GRB 990123 overlaps with the MeV radiation front. Therefore, the optical-emitting electrons must also produce GeV-TeV emission by inverse Compton scattering of MeV photons. The ultra–high-energy flash can be much stronger than its optical counterpart. We also note that Compton cooling by MeV photons immediately terminates the optical emission unless the fireball Lorentz factor exceeds 10^3. Severe Compton losses may explain the nondetections of optical flashes in several long GRBs. Such failed optical flashes should be especially efficient GeV producers and likely to develop $e^{\pm}$ cascades. This probably happened in GRB 941017, and its mysterious high-energy component is well explained by Compton upscattering of GRB photons at the fireball deceleration radius. The proposed mechanism of GeV emission should not work for short GRBs that early decouple from the fireball and avoid interaction with the electrons in the deceleration flash. Observations by *Swift* and the *Gamma-Ray Large Area Telescope* will provide an opportunity to test these expectations. The existing data for GRB 990123 already impose interesting constraints on the explosion.

Subject headings: cosmology: miscellaneous — gamma rays: bursts — radiation mechanisms: nonthermal — shock waves

1. INTRODUCTION

Prompt optical observations of gamma-ray bursts (GRBs) are challenging because they require a quick pointing of an optical telescope or patrolling the whole sky with good angular and temporal resolutions. Nevertheless, about 10 bursts have been observed in 10–100 s time by the Robotic Optical Transient Search Experiment (ROTSE) instrument (Akerlof et al. 2000; Kehoe et al. 2001). In only one of them, GRB 990123, a bright optical flash was detected, which reached a peak of ninth magnitude at 40–50 s after the beginning of the GRB (Akerlof et al. 1999). The peak overlapped with the main MeV burst, however, was interpreted as a separate emission component because it had a different light curve and showed a tail ~10 times longer than the MeV burst. Similar tails of optical flashes were caught in a few other bursts at times less than 10^3 s (Fox 2002; Fox et al. 2003). Such flashes are expected from the reverse shock in the GRB fireball (Mészáros & Rees 1993; Sari & Piran 1999) or the early forward shock in the external medium (Beloborodov 2004). It was unclear, however, why they were not detected in most of the bursts observed by ROTSE (Akerlof et al. 2000; Kehoe et al. 2001), and possible reasons have been discussed (e.g., Kobayashi 2000; Nakar & Piran 2004).

2. OPTICAL FLASH

The optical flash is interpreted as synchrotron emission of relativistic electrons injected in a magnetic field B. Emission from electrons with Lorentz factors γ_e in the fluid frame peaks at frequency $\nu_{\rm fluid} \approx 0.2(eB/m_e c)\gamma_e^2$ (assuming isotropic pitch-angle distribution). The corresponding observed frequency is modified by the Doppler effect and a cosmological redshift of the burst, $\nu \approx (1+z)^{-1}\Gamma\nu_{\rm fluid}$, where Γ is the fluid Lorentz factor and z is the redshift. The characteristic γ_e that gives emission at the observed frequency ν is

$$\gamma_e(\nu) = \left[\frac{5m_e c\nu(1+z)}{\Gamma eB}\right]^{1/2}. \tag{1}$$

The energy density of the magnetic field, $w_B = B^2/8\pi$, is a fraction of the total plasma energy in the emission region, w. As is customary, we parameterize B by $w_B = \epsilon_B w$.

If the flash is caused by the fireball interaction with an ambient medium, w is estimated from the jump condition at the forward shock: $w = 4\Gamma^2 n m_p c^2$, where n is the ambient density. The energy density is about this value everywhere between the forward and reverse shocks (while ϵ_B may be significantly different on the two sides of the contact discontinuity). One then finds

$$\gamma_e(\nu) \approx 3 \times 10^2 (1+z)^{1/2}\nu_{15}^{1/2}\Gamma_2^{-1}(\epsilon_B n)^{-1/4}, \tag{2}$$

where n is expressed in units of cm^{-3}.

The observed flash in GRB 990123 emits $\sim 10^{-3}$ of the GRB energy and then decays with time as a power law of index 1.6–2, which extends to at least 10^3 s. This decay was interpreted as a result of adiabatic cooling of the injected relativistic electrons in the expanding fireball, which requires the synchrotron cooling to be relatively slow,

$$t_s(\gamma_e) = \frac{3m_e c}{4\sigma_{\rm T} w_B \gamma_e} > t_{\rm exp} = \frac{R}{c\Gamma}. \tag{3}$$

Here t_s is the synchrotron cooling timescale and $t_{\rm exp}$ is the expansion time at a radius R (the timescale of adiabatic

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cooling); t_s and $t_{\exp}$ are measured in the fluid frame. Using equation (2), we can rewrite this condition as

$$\epsilon_B n < 2 \times 10^{-2}(1+z)^{-2/3}\nu_{15}^{-2/3}R_{17}^{-4/3}. \qquad (4)$$

3. INVERSE COMPTON COOLING BY MeV RADIATION

The peak of the optical flash in GRB 990123 arrived in the middle of the prompt burst. It implies that most of the flash-emitting electrons were exposed to the MeV photons. This is so even if the MeV source is "patchy"—the photons would propagate and fill the observable part of the fireball R/Γ where the flash could come from.

3.1. *The Slow-cooling Condition*

The energy density of the 0.1–1 MeV photons in the flash region is given by

$$w_\gamma = \frac{E_\gamma}{4\pi R^2 \Delta \Gamma^2}, \qquad (5)$$

where E_γ is the isotropic equivalent of the burst energy, $\Delta = (1+z)^{-1}ct_b$ is the thickness of the MeV radiation front, and t_b is the observed GRB duration. The radiation density w_γ is measured in the fluid frame where the photon energy is $\varepsilon_{\rm fluid} = \varepsilon/\Gamma \sim$ keV. Electrons with $\gamma_e(\nu) \sim 10^2$–10^3 will upscatter the photons with the Thomson cross section if $\varepsilon_{\rm fluid} < m_e c^2/\gamma_e(\nu)$, which is comparable to or exceeding the main peak of the GRB spectrum, and therefore a significant fraction of w_γ will efficiently cool the flash-emitting electrons. A slow-cooling model of the flash must satisfy the condition

$$t_{\rm IC}(\gamma_e) = \frac{3m_e c}{4\sigma_{\rm T} w_\gamma \gamma_e} > t_{\exp}. \qquad (6)$$

We note that Compton cooling by optical radiation is much weaker compared with the upscattering of MeV photons because the energy of optical radiation is relatively small: $w_O \sim 10^{-3} w_\gamma$ in GRB 990123.

Substitution of $\gamma_e(\nu)$ from equation (2) gives

$$\frac{t_{\rm IC}(\nu)}{t_{\exp}} = 4 \times 10^{-3}\Gamma_2^4 \nu_{15}^{-1/2}(1+z)^{-1/2}(\epsilon_B n)^{1/4}E_{\gamma,54}^{-1}\Delta_{12}R_{17}. \qquad (7)$$

The flash in GRB 990123 peaks on a short timescale $t_{\rm obs} <$ 100 s and therefore must be emitted at a radius not larger than the deceleration radius of the blast wave. This radius is defined by[2] $m = E/2c^2\Gamma^2$, where E is fireball energy (left over after it emits the prompt GRB) and m is the swept-up ambient mass. For a medium with density profile $n(R) \propto R^{-k}$, the mass within a radius R is $m(R) = [4\pi/(3-k)]R^3 n m_p c^2$, which gives

$$R_{\rm dec} = \left[\frac{(3-k)E}{8\pi n m_p c^2 \Gamma^2}\right]^{1/3} = 1.4 \times 10^{17}(3-k)^{1/3}E_{54}^{1/3}n_{\rm dec}^{-1/3}\Gamma_2^{-2/3} \text{ cm}, \qquad (8)$$

[2] This definition assumes that half of E is dissipated by the reverse shock in the fireball.

$$\frac{t_{\rm IC}(\nu)}{t_{\exp}} = 6 \times 10^{-3}\Gamma_2^{10/3}\nu_{15}^{-1/2}(1+z)^{-1/2}(3-k)^{1/3} \times E_{54}^{1/3}\epsilon_B^{1/4}n_{\rm dec}^{-1/12}E_{\gamma,54}^{-1}\Delta_{12}\left(\frac{R}{R_{\rm dec}}\right)^{1-k/4}, \qquad (9)$$

where $n_{\rm dec} = n(R_{\rm dec})$. Substituting here the observed parameters of GRB 990123—$z = 1.6$, $E_\gamma \approx 2 \times 10^{54}$ ergs, and $\Delta \approx 10^{12}$ cm—one finds that the electrons emitting in the optical band are slowly cooling if

$$\Gamma > 550(3-k)^{-1/10}\epsilon_B^{-3/40}n_{\rm dec}^{1/40}\left(\frac{E}{E_\gamma}\right)^{-1/10} \times \left(\frac{R}{R_{\rm dec}}\right)^{-3/10(1-k/4)}\left(\frac{E_\gamma}{2\times 10^{54}}\right)^{1/5}\Delta_{12}^{-3/10}. \qquad (10)$$

Since the flash radius cannot exceed $R_{\rm dec}$, we conclude that the slow-cooling condition can be satisfied in GRB 990123 if the Lorentz factor of the emitting region exceeds $500\epsilon_B^{-3/40}$.

An additional relation between Γ and R is given by the known arrival time of the flash, $t = (1+z)R/2\Gamma^2 c \approx 50$ s. Combined with $R \le R_{\rm dec}$ and condition (10), this gives a strong constraint on the deceleration radius, $R_{\rm dec} > 3.5 \times 10^{17}(3-k)^{-1/5}\epsilon_B^{-3/20}n_{\rm dec}^{1/20}(E/E_\gamma)^{-1/5}$ cm, and ambient density,

$$n_{\rm dec} < 10^{-2}(3-k)^{3/2}\epsilon_B^{1/2}\left(\frac{E}{E_\gamma}\right)^{3/2} \text{ cm}^{-3}. \qquad (11)$$

3.2. *Reverse-Shock Model*

The reverse shock can accelerate electrons with a power-law distribution and a mean Lorentz factor

$$\bar{\gamma}_e = \frac{m_p}{m_e}\frac{\epsilon_e}{2}\left(\frac{\Gamma_{\rm ej}}{\Gamma} + \frac{\Gamma}{\Gamma_{\rm ej}} - 2\right). \qquad (12)$$

Here ϵ_e is the fraction of postshock energy density that is carried by the accelerated electrons, and $\Gamma_{\rm ej} > \Gamma$ is the Lorentz factor of the preshock fireball. Since $\bar{\gamma}_e$ is comparable with $\gamma_e(\nu)$ for $\nu \sim 10^{15}$ Hz, the reverse shock is expected to be an efficient producer of optical radiation (Mészáros & Rees 1993; Sari & Piran 1999).

The reverse-shock emission peaks at $R \approx R_{\rm dec}$ and then gradually decays if the accelerated electrons cool down slowly, on the expansion timescale. Besides the slow-cooling conditions (eqs. [4] and [10]), we note two other requirements:

1. The bulk of MeV photons can overlap with the reverse-shock emission as observed only if they are produced inside the fireball. This agrees with the idea of internal dissipation as a source of prompt γ-rays (e.g., Rees & Mészáros 1994). The short-timescale variations in the prompt γ-rays indicate that they are produced at a radius $R_\gamma \ll R_{\rm dec}$. Then the MeV front gets strongly collimated by the time it reaches $R_{\rm dec}$ and propagates with velocity c in the fireball frame.
2. The reverse shock can reach an emission peak before the MeV front fully overtakes it only if the shock is relativistic—a nonrelativistic shock would cross the fireball on a longer timescale, and its emission would lag behind the γ-rays.

This implies that $\Gamma_{\rm ej}$ in GRB 990123 is even higher than required by the slow-cooling condition: $\Gamma_{\rm ej} > 2\Gamma > 10^3\epsilon_B^{-3/40}$.

4. GeV-TeV FLASH

Inverse Compton scattering of MeV radiation in the flash region produces ultra–high-energy photons. The prompt GRB spectrum usually peaks at $\varepsilon_p = 0.1$–1 MeV, which translates to $\varepsilon_p/\Gamma \sim$ keV in the fluid frame. This peak can be upscattered efficiently by electrons with

$$\gamma_e < \gamma_e^* = \Gamma \frac{m_e c^2}{\varepsilon_p} \sim \Gamma, \tag{13}$$

above which the Compton cross section is reduced by the Klein-Nishina correction. The energy of upscattered photons $\varepsilon_{\rm IC} \sim \gamma_e^2 \varepsilon_p$ can extend to $\varepsilon_{\rm IC}^* \sim \Gamma^2 \varepsilon_p$, which is in the GeV-TeV range.

The upscattered photons will avoid γ-γ absorption and escape the source if its optical depth $\tau_{\gamma\gamma}(\varepsilon_{\rm IC}) < 1$. The optical depth seen by photons $\varepsilon_{\rm IC} = \varepsilon_{\rm IC}^*$ is

$$\tau_{\gamma\gamma}(\varepsilon_{\rm IC}^*) \sim 0.1\, \frac{w_\gamma}{\varepsilon_p}\, \sigma_{\rm T} R \approx 0.1\, \frac{t_{\rm exp}}{t_{\rm IC}(\gamma_e^*)}. \tag{14}$$

For $\varepsilon_{\rm IC} < \varepsilon_{\rm IC}^*$, $\tau_{\gamma\gamma}$ is reduced as $(\varepsilon_{\rm IC}/\varepsilon_{\rm IC}^*)^\beta$, where β is the slope of the prompt radiation spectrum at $\varepsilon > \varepsilon_p$. Since γ_e^* is not much different from $\gamma_e(\nu)$ for optical ν, one concludes that a slow-cooling optical flash, $t_{\rm IC} > t_{\rm exp}$, is also γ-γ transparent.

The emerging luminosity of ultra–high-energy photons is much higher than the synchrotron luminosity if Compton losses dominate over synchrotron losses, i.e., if $w_\gamma \gg w_B$. The ratio of the two luminosities is given by

$$\frac{L_{\rm UHE}}{L_s} = \frac{w_\gamma}{w_B} \sim \frac{1}{\epsilon_B}\frac{E_\gamma}{E}\left(\frac{R}{R_{\rm dec}}\right)^{-2}. \tag{15}$$

(Here we assumed $R_{\rm dec} \sim 2\Gamma^2\Delta$, which is valid if the reverse shock is at least mildly relativistic.) The $L_{\rm UHE}$ is emitted as long as the flash overlaps with the MeV radiation front. It ends when the blast wave begins to decelerate and the MeV front fully overtakes it.

GRBs with Lorentz factors smaller than 10^3 will have fast-cooling flashes, $t_{\rm IC} < t_{\rm exp}$. Then the optical emission is suppressed. The fast Compton cooling is a possible reason of the nondetections of optical flashes in long GRBs observed by ROTSE.

In the fast-cooling case, $t_{\rm IC}(\gamma_e^*) \ll t_{\rm exp}$, the upscattered γ-rays may not avoid the γ-γ absorption (see eq. [14]). Then an $e^\pm$ cascade develops from γ_e^* to a lower $\gamma_{e,1}$ such that $\tau_{\gamma\gamma}(\varepsilon_{\rm IC,1} = \gamma_{e,1}^2\varepsilon_p) \sim 1$. The pairs resulting from this cascade cool to even lower $\gamma_{e,c}$ such that $t_{\rm IC}(\gamma_{e,c}) = t_{\rm exp}$. Most of the ultra–high-energy luminosity should then emerge at energies $\sim\varepsilon_{\rm IC,1}$. The slope of the inverse Compton spectrum is $-\frac{1}{2}$ between $\varepsilon_{\rm IC,c} \sim \gamma_{e,c}^2\varepsilon_p$ and $\varepsilon_{\rm IC,1}$ (the fast-cooling inverse Compton spectrum). The slope below $\varepsilon_{\rm IC,c}$ should approximately equal the slope of the prompt GRB spectrum at $\varepsilon < \varepsilon_p$.

If the flash emits a fraction $\epsilon_{\rm flash}$ of the fireball energy E, the ratio of the flash energy to the prompt GRB energy is $E_{\rm flash}/E_\gamma = \epsilon_{\rm flash}(E/E_\gamma)$. This ratio can exceed unity if the radiative efficiency of the flash exceeds that of the prompt GRB.

The upscattered γ-rays have a collimation angle $\theta \sim 1/\Gamma$ and therefore lag behind the unscattered prompt radiation [which has a smaller collimation angle $\theta = (R_\gamma/R_{\rm dec})\theta_\gamma$, where R_γ is the radius of prompt emission and θ_γ is its initial collimation angle]. The resulting delay of high-energy γ-rays, $\delta t \sim (1+z)R_{\rm dec}/\Gamma^2$, is comparable with the duration of the prompt burst t_b, and the duration of the high-energy flash $t_{\rm UHE} \sim t_b + \delta t$ is a few times longer than t_b. The angular dispersion of high-energy photons also mixes up their arrival times and washes out short-timescale variability. This is a signature of upscattering at a large radius $R_{\rm dec} > R_\gamma$, which contrasts with the variable prompt radiation.

4.1. *GRB 941017*

A high-energy flash was observed in GRB 941017 by the *Compton Gamma Ray Observatory* (González et al. 2003). It lasted about 200 s, which is 2.5 times longer than the prompt GRB, and had a hard spectral slope $\alpha \approx 0$ at 10–100 MeV. Possible inverse Compton models were examined by Granot & Guetta (2003) and found to be inconsistent with the data. The best proposed candidate was a reverse-shock emission (synchrotron self-Compton), which had the correct timing but still had a problem in explaining the spectral slope. Stern & Poutanen (2004) considered prompt GeV emission from continuously heated electrons in the fireball, and Dermer & Atoyan (2004) proposed a model involving acceleration of hadrons to ultrahigh energies.

The data are consistent with the high-energy flash mechanism described above. All three expected features are observed: (1) the flash lasted a few times longer than the prompt MeV burst; (2) it did not show significant variability in the studied time bins; and (3) it peaked above the observed range $\varepsilon <$ 200 MeV, and the observed spectrum had approximately the same slope as the low-energy part of the prompt spectrum, consistent with the upscattering of the prompt 0.1 MeV photons. The energy of the high-energy flash exceeds E_γ by at least a factor of 3, which points to a relatively low radiative efficiency during the prompt burst and a high radiative efficiency during the deceleration flash.

The data are consistent with an upscattering electron population that peaks at the cooling Lorentz factor $\gamma_{e,c} \sim 10$. The electrons can be injected with higher $\gamma_e \sim 10^2$–10^3, then undergo $e^\pm$ cascade to $\gamma_{e,1} \sim 10$–100, and cool down to $\gamma_{e,c} \sim 10$. The peak of the high-energy spectrum is weakly constrained by the data; however, it is probably not far from 1 GeV—otherwise the energy of the upscattered component would be very high.

5. CONCLUSIONS

When the optical flash overlaps with the prompt MeV front, like it does in GRB 990123, its main cooling mechanism is inverse Compton scattering of the MeV photons rather than synchrotron (or synchrotron self-Compton) emission. This strong cooling tends to terminate the flash. Only if the fireball has a high $\Gamma \gtrsim 10^3$ is Compton cooling slow compared with the fireball expansion and consistent with the observed tail of the flash in GRB 990123. This condition can be translated to an upper bound on the ambient density $n \lesssim 0.1\epsilon_B^{1/2}$ cm^{-3} (eq. [11]). If the flash was produced by the reverse shock in the fireball, the data require the shock to be relativistic and the prompt MeV burst to originate inside the fireball.

In GRBs with typical Lorentz factors $\Gamma < 10^3$, the flash is fast cooling as long as it overlaps with the MeV radiation. The accelerated electrons quickly emit their energy by upscattering the MeV photons and produce a bright GeV flash, likely with the development of an $e^{\pm}$ cascade. The low-energy slope of the upscattered spectrum is the same as the low-energy slope of the prompt GRB; at higher energies it changes to $-\frac{1}{2}$ and is cut off by γ-γ absorption in the source. The temporal behavior of the high-energy flash differs from the prompt GRB: the short-timescale variability is washed out, and the arrival time is extended by a factor of a few. These features are observed in the high-energy component of GRB 941017.

One expects a clear spectral separation of the upscattered component from the prompt 0.1–10 MeV radiation. It is likely to peak well above 1 GeV in most cases. GRB 941017 appears to be a rare case where the peak is comparable with 1 GeV, which makes the upscattered component well visible at 10–100 MeV. This rare case can be explained by a relatively low $\Gamma = 100$–200, which places the cooling Lorentz factor at $\gamma_{e,c} \sim 10$. The special character of this burst is confirmed by the fact that a similar component was not found in 25 other bursts studied by González et al. (2003). The *Gamma-Ray Large Area Telescope* should be able to observe the typical upscattered flashes at energies up to 100 GeV.

The overlapping of the decelerating fireball with MeV photons may not take place in all GRBs. The velocity of hot gas in the fixed frame is $c(1 - 1/2\Gamma^2)$, and the MeV front completely overtakes it at a radius $R_\Delta = 2\Gamma^2\Delta$. The overlapping does not occur if $R_\Delta < R_{\rm dec}$, which requires the observed duration of the MeV front

$$t_b < 10 \left(\frac{\Gamma}{300}\right)^{-2} R_{\rm dec,\,17} \frac{(1+z)}{2} \ \text{s}. \tag{16}$$

The class of short GRBs with durations $t_b \sim 0.1$ s can satisfy this condition and avoid the Compton cooling by MeV photons; the condition can also be met by long bursts with modest Γ. Then an optical flash can be produced without a significant GeV-TeV counterpart.[3]

ROTSE observations of three short bursts impose upper limits on their optical flashes (Kehoe et al. 2001). The most stringent upper limit was obtained for GRB 980527 ($t_b = 0.09$ s), where optical energy emitted at 15 s after the burst did not exceed $\sim 10^{-5}$ of the GRB energy. It can, however, be that the deceleration time for this burst was short, $R_{\rm dec}/\Gamma^2 \ll 15$ s, and the flash was not seen because it was observed too late.

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[3] Condition (16) implies a nonrelativistic reverse shock, and the prompt photons leave the fireball before the shock crosses it.

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